Managing Island Biotas: Can Indigenous Species Be Protected From Introduced Predators Such as the Brown Treesnake?

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Due to their inability to cross large stretches of ocean, amphibians, large reptiles and non-volant terrestrial mammals are naturally absent from oceanic islands. The species of birds, bats and small lizards that do reach oceanic islands often develop "island tameness"—a lack of wariness toward humans and other predators (Quammen 1996). Numerous examples exist of unwary island species suffering catastrophic population declines when humans introduce generalist predators to such islands (Ebenhard 1988).

A particularly well-known example is that of the U.S. island of Guam, where almost all native vertebrates have either suffered population declines or been extirpated as a result of the accidental introduction of the brown treesnake, *Boiga irregularis* (Savidge 1987, Rodda et al. 1998b). Although larger numbers of species have been lost as a result of single introductions elsewhere (Goldschmidt et al. 1993), the Guam snake debacle stands out as extraordinary in the wide range of taxa affected (birds, mammals and reptiles) and completeness of the loss (virtually all native non-aquatic vertebrates). At present, Guam has lost all breeding populations of seabirds, 10 of 13 species of native forest birds (the three surviving forest bird populations are all endangered); 2 of 3 native mammals (the third species has not reproduced effectively in the last decade); and 6 of 10 to 12 species of native lizards. Although one full bird species is globally extinct, two of the bird species are being maintained by captive propagation, and most of the other birds, mammals and lizards are represented by similar populations (sometimes different subspecies) on other islands. Thus, populations similar to the original Guam populations could be restored to Guam if snake populations were controlled.

In addition to these wildlife losses, the brown treesnake on Guam is responsible for power outages (1,400 recorded from 1978 to 1996) (Fritts and Chiszar 1998), loss of domestic and pet animals (Fritts and McCoid 1991) and potentially fatal envenomations of human babies (Fritts and McCoid 1998). Furthermore, the snake has been accidently transported from Guam to a variety of locations worldwide (Australia, Diego Garcia, Kwajalein, Oahu, Okinawa, Pohnpei, Rota, Saipan, Spain, Texas and Tinian) (Fritts et al. 1998). On Saipan and Oahu (Hawaii), brown treesnakes have appeared on numerous occasions, indicating a high risk of colonization. These American islands have large numbers of endangered birds, suggesting a high cost to global biodiversity if the snake were to become established.

The goals of brown treesnake management are to keep snakes from adversely affecting native wildlife and humans on Guam, and to keep snakes from spreading to other islands or continents. Research aimed at meeting these needs has been reported in nearly 400 scientific and lay publications (Imamura 1997, Rodda et al. 1998e). Good management techniques combine good ecological understanding with cultural sensitivity. In addition to scientific studies of the snake, our long-term experiences on Guam (now more than 30 person-years) has provided an opportunity to assess the social and cultural constraints that would apply to prospective snake management activities. This scientific and cultural experience is the basis for the following assessments of the biological, financial, practical and social feasibility of various prospective management tools.

Scales and Tools

Protection of electrical power systems from snake-caused outages requires only that snakes be segregated from high-voltage wires. Efforts to keep snakes from spreading to other islands are similarly limited in geographic scope, it being necessary only to keep the snakes off ships or aircraft leaving Guam. Wildlife conservation, however, requires reduction of snake populations over large geographic areas. Thus, the utility of any snake control technique depends on the geographic scale at which it can be used.

Four basic types of solutions have been proposed for dealing with Guam's snake problem. In order of decreasing scale, these are: 1) eradicate brown treesnakes from Guam; 2) greatly reduce snake populations permanently throughout Guam; 3) control snake populations over areas large enough for endangered species restoration (0.2 to 20 square miles [50-5,000 ha]); and 4) control snakes in very small areas (cargo handling yards, transportation craft, etc.) to prevent further spread.

Techniques that have been used or suggested for brown treesnake control at these scales fall into seven major categories: exclusion, direct capture, trap capture, habitat modification, chemical population control, self-sustaining biocontrol and chronic biocontrol. Before evaluating the utility of each at different geographic scales, we will describe all of them.

Exclusion

Various thermal, chemical, electrical and mechanical approaches have been developed for keeping brown treesnakes out of target areas. For example, snakes can be excluded from power lines by using smooth poles (concrete is widely used in Guam), attaching guy wires well above or below the conductors, or using conical guards on the guy wires (Fritts and Chiszar 1998). Individual nest trees may be protected by the combination electrical and mechanical barrier developed by Aguon et al. (1998). Snakes can be excluded from mid-scale areas (wildlife habitat) by a variety of designs of snake-proof fencing (Campbell 1998, Rodda et al. 1998a, Perry et al. 1997).

Although registered chemical barriers have not been found successful for durable exclusion of snakes (McCoid et al. 1993), chemical repellents have been successfully tested for the expulsion of snakes from hiding places (L. Clark personal communication: 1997). These might be useful for eliminating snakes from hiding places in cargo. Fumigants are also available for killing snakes in enclosed spaces (Savarie et al. 1998, Savarie and Bruggers 1998). Two exclusion techniques that are not yet developed are microclimate repellents and lethal microclimate exclusion. An example of microclimate repellents would be lights placed over aircraft parked overnight and bright enough to repel the normally nocturnal brown treesnake. Preliminary tests of this tactic have not supported this possibility, however (C. Caprette personal communication: 1997). Lethal microclimate exclusion might include heating a shipping container to a temperature above the brown treesnake's critical thermal maximum, for example. Under Guam's tropical sun, this may be as simple as leaving a closed container on the dock for 24 to 48 hours.

Direct Capture

Trained searchers are presently being used to conduct visual searches for brown treesnakes in high-risk areas. Chain-link fences are a preferred substrate for visual searches, as the snakes are readily seen against the regular and transparent pattern of chain-links (Rodda 1991). In more complex natural environments, however, searchers vary significantly in their ability to detect the cryptic brown snakes (Rodda and Fritts 1992, Rodda 1993). Even large introduced deer routinely slip through lines of searchers in the dense forests found on Guam (H. Hirsh personal communications: 1998); our population analyses showed that the best capture rate achieved by highly trained searchers in areas of Guam gridded with trails was less than 10 percent of the population and often is around 1 percent. Mishima et al. (1978) were unable to significantly reduce populations of a snake from a small island off Okinawa using trained searchers for several months. Dog-aided searches are used extensively to screen cargo in Guam, Saipan and Hawaii (Engeman et al. 1998, S. Vogt personal communication: 1998). However, such searches are not conducted in natural environments, where dogs are distracted by a myriad of natural odors (Imamura 1998).

Direct capture using volunteers has been suggested by those unfamiliar with the Guam environment. As a variant, use of economic incentives (prizes, bounties, commercial sales) has been advocated. However, a month-long snake roundup on Guam (with individual prizes valued at more than $15,000) induced only three pairs of searchers to collect snakes seriously, with a total yield amounting to less than 0.2 percent of the island's snakes (Rodda et al. 1998d). A risk of such commercialization is that of spread of snakes to other islands. If the snakes became economically valuable on Guam, unthinking persons may spread the snakes to additional islands for additional monetary rewards. This may have happened with the elegant pitviper (*Trimeresurus elegans*) on Okinawa (Ota 1998). For these reasons, economic incentives are no longer under serious consideration for management of the brown treesnake.

Trap Capture

Traps are in use for both brown treesnakes and their prey (e.g., pigeons, rats). At the present time, prey traps are being used to locally minimize the presence of prey odors that might draw snakes into high-risk sites such as airports. Extant snake traps utilize natural prey as attractants (mice are protected in cages within snake traps), but other attractants may be possible. For example, it might be possible to find a pheromone that would attract snakes (Mason 1998). The primary advantage of a pheromonal attractant is that behavioral resistance to such an attractant would not be likely to develop. The greatest weakness is that the class of snakes most likely to be caught in a pheromone trap is adult males, which constitute only a small fraction of brown treesnake populations on Guam and are of the least significance from the standpoint of blocking accidental dispersal or reducing population recruitment. In addition, the extant snake pheromone induces courtship behavior when it is touched, but has not been shown to draw a snake into a trap. A more promising approach would be to discover an artificial attractant that used prey cues (motion, image, odor, vibration, etc.) to entice snakes into traps without having to maintain live animals in the traps. This approach has been studied by a large number of Japanese researchers over the last two decades (Hattori et al. 1998), with uniformly unfavorable results. Recent work with isolated odors has produced equivalently disappointing results with brown treesnakes (Shivik and Clark in press). It is theoretically possible to make a trap whose attraction is that it provides an ideal hiding place for a snake (a refugium trap), but we are unaware of any progress in this area.

Habitat Modification

Brown treesnakes use a wide range of habitats, including subterranean, grassy, shrubland and forest areas. During the daytime, brown treesnakes rarely occur and go undetected in short mowed grass or asphalt, however. Thus, the elimination of forest around high-risk sites such as cargo facilities provides a degree of protection against accidental dispersal of snakes.

Chemical Population Control

A variety of oral and dermal toxicants are known for brown treesnakes (Savarie and Bruggers 1998). No practical method has yet been developed to entice substantial numbers of snakes to ingest or crawl in these compounds, however. Thus, the key will be to find a suitable attractant and delivery system. Live mice are very successful attractants and are in general use for traps, but their use for attracting snakes to toxicant bait stations appears prohibitively expensive. Much effort has been expended on artificial attractants of brown treesnakes, but with no practical lures yet developed. Japanese research on snake attractants extends over several decades (primarily for the snake *Trimeresurus flavoviridis*), with similar lack of success (Nishimura 1998). To date, most effort has focused on the use of prey or prey odors, but pheromones and optimal refugia may also make suitable attractants.

Any toxicant must be unavailable to non-target species such as endangered birds and pets, and poisoned snakes must not be toxic to carrion-eaters such as the endangered Mariana crow (*Corvus kubaryi*). If bait stations or toxic baits are to be distributed from aircraft (to reach remote areas and private land), these must be biodegradable yet protect the toxin from exposure to conditions (sunlight, water) which might cause excessively rapid loss of effectiveness.

In theory, one could deliver a dermal toxicant in aerosol form, such as is sometimes used for pest insects. With the exception of use in confined spaces (e.g., shipping containers), we are not aware of any research on this possibility for brown treesnakes. A toxicant could be in the form of a chemosterilant rather than an acute toxin, but this has not been investigated. A drawback of chemosterilization is that no one knows how to do it in snakes. If the sterility was dependent on continuous or periodic exposure to the contraceptives, it would be necessary to administer the toxicant over more than a decade to ensure that treated animals died of old age before resuming reproduction. An even more subtle use of a toxicant would be to stress the snakes in some way (stress inducers) that would cause the snakes to reduce reproductive output or possibly expire from other proximate causes. For example, suppose that a drug were found that caused snakes to shed their skins too frequently. Shedding is a physiologically and nutritively expensive activity that interrupts snake foraging for a week or more. Excessive shedding might limit snake foraging on endangered species or even cause snakes to starve at certain times. This is but a theoretical possibility, however, as no one has identified a suitable mechanism for stress induction, and we are unaware of any research on this possibility. Finally, one could chemically reduce snake populations by chemically limiting populations of snake prey (food supply seems to be the primary limiting factor in brown treesnake populations [Rodda et al. 1998c]). This can be done on a small scale, but is not anticipated on a landscape scale, as the difficulties of holding down rat populations have been found to be excessively expensive (Mishima et al. 1998), and the other prey would appear to be even less practical to control on a large scale.

Self-sustaining Biocontrol

Classical biocontrol involves the colonization of the habitat with an introduced enemy of the target species or its prey. Enemies are diseases, parasites or macropredators. The most effective control agent is likely to be one with which the host organism has had no evolutionary interactions (e.g., an African insect attacking a South American plant). Because all predator-based attempts at controlling vertebrates on islands have ended in either failure or catastrophic destruction of non-target species, the macropredator approach is no longer considered acceptable (Davis et al. 1976, Waage and Mills 1992, Howarth 1998). Brown treesnake parasites (Telford 1998) and diseases (Nichols personal communication: 1997) are being researched, although neither approach has been used successfully for permanent suppression of vertebrates (vertebrates develop immunity [Nokes 1992]). A potential advantage of using parasites to control brown treesnakes is that current evidence suggests low genetic diversity in the Guam snake population (L. Rawlins personal communication 1998).

The track record of pathogens for successful vertebrate control is limited to a single pathogen (myxoma virus) with a single host (rabbits) that yielded only temporary control. The virus evolved reduced virulence, as expected

(Holmes 1982). In other vertebrate pest management cases, the problems have been lack of host-specificity or lack of virulence to start with, often because the disease was from the host's native range and the host had co-evolved with the disease. There are no examples of successful control of vertebrates with parasites, perhaps because parasite systems tend to be highly co-evolved, often requiring intermediate hosts that are not present in the extralimital population's environment (Nichols personal communication: 1992).

There are three other issues relevant to the brown treesnake on Guam: 1) next to nothing is known about snake epidemiology, and what is known suggests that high-virulence diseases of brown treesnakes are not present in native range (e.g., Ross and Marzec 1984); 2) it is very difficult to test for virulence of pathogens on snakes in a laboratory, as the laboratory environment causes immunosuppression in reptiles (Jarchow 1989); and 3) because brown treesnakes readily get on ships and planes leaving Guam, any induced ophidian epizootic would be expected to spread to other islands and continents, potentially causing astronomical economic and ecological losses to non-target ecosystems and agricultural economies. Any vertebrate pathogen/parasite release on Guam should be subjected to intense scrutiny and would be reflexively viewed with hostility by many Pacific islanders. In principal, one could also consider introduction of predators or parasites on the prey of brown treesnakes, as prey reduction would probably induce population declines in the snake. However, any prospective controllers of brown treesnake prey would probably themselves constitute a new and valuable source of food for the snakes and would also be a threat to the endangered wildlife whose restoration was the goal of brown treesnake control. For example, it is likely that the irruption of the shrew *Suncus murinus* sharply limited skink numbers after the shrew was introduced to Guam in 1953. Subsequently, snake predation on the shrew fueled the irruption of the snake and incidently released suppressed skink populations which rebounded, providing another key food source for snakes (Fritts and Rodda 1998). Any biocontrol of prey is likely to adversely impact lizard species that are either not a target species or are endangered themselves. Thus, biocontrol of brown treesnake prey is not being pursued, to the best of our knowledge.

Chronic Biocontrol

Biocontrol agents have also been used on a recurring basis to periodically alter the densities of selected species. For example, farmers may purchase large numbers of predatory ladybird beetles to combat aphid infestations. This use of biopesticides is not being developed for brown treesnakes, as far as we know. Theoretically, one could also inhibit brown treesnake reproduction by inundative releases of sterile males, but no one has envisioned a practical way to produce the large numbers of males that would be needed.

Applications

For simplicity, we listed the various control approaches individually. However, all brown treesnake management plans call for integrated pest management (e.g., The Brown Tree Snake Control Committee 1996, Campbell et al. 1998). In the following section, we mention only a few of the techniques under the categories of "Best tools" "Leads worth pursuing" and "Seductive losers." In the latter, we explain why certain techniques would not be worth pursuing, although they might at first appear to be. Techniques are grouped according to geographic scale, with the largest scale solutions appearing first.

Largest Scale: Eradicate Brown Treesnakes From Guam or Greatly Reduce Snake Populations Permanently Throughout Guam

Best tools. None.

Leads worth pursuing. Chemical population control is theoretically usable for pest eradication, but successful examples to date have been limited to readily poisoned species such as rats (which cannot regurgitate bait, are easily poisoned and must eat daily) on very small islands (less than 4 square miles [1,000 ha]). The prospects for eradication of snakes on a 209-square mile (54,100 ha) island are remote. The potential for depressing snake populations is better, but non-eradication treatments would be required periodically in perpetuity. In this case, the cost of application becomes a critical value. Even a slight social cost (e.g., perceived threat to water quality) is likely to result in objections by Guamanians who were born after the disappearance of native wildlife or have become inured to the presence of the snake. The last time any pesticide was used widely on Guam (in 1975, to forestall the introduction of dengue fever, an occasionally fatal disease) treatment cost $63,000 per application and was quickly halted (Haddock et al. 1979). Under a cost scenario favorable for snake toxicants (assume bait stations cost $1 to purchase and place, and are needed every 82 feet or 25 meters), the financial cost for islandwide control would be about $500,000 per application.

Biological control by a generalist disease is unacceptable due to non-target species losses. Assuming that a suitably specific and virulent candidate could be found, it might take an additional 5 to 10 years ($1-2 million?) for regulatory hurdles and public acceptability to be obtained. A host-specific disease is unlikely to depress snake numbers greatly, because the pathogen would be unable to find a host when the obligate hosts became rare.

Seductive losers. Trap capture islandwide is not practical. Much of Guam is topographically inaccessible or is in private hands and, thus, is off limits to ground control activities. Even if this were not the case, eradication would require trapping to occur simultaneously throughout the island. Cost of traps and personnel would be roughly $200 million (10 traps per acre; 133,683 acres = 25 traps per hectare; 54,100 hectares = more than 1 million traps; 1 federal employee per 150 traps; the local personnel requirements in effect for snake trapping are much higher).

Biocontrol by macropredation has a high probability of causing another island catastrophe. The king cobra is the one macropredator within the native range of the brown treesnake that is known to specialize on eating snakes. No better predators are known, and no one would seriously consider introducing another snake—especially this one.

Snake chemosterilants are not even known at a physiological level, much less an ecological one. More importantly, however, if an attractant can be devised to reliably bring snakes to the delivery system, why not use poison to kill the snakes outright, thereby reducing dispersal hazards?

Mid-scale: Control Snakes Over Areas Large Enough for Populations of Some Endangered Species

Best tools. Exclusion technology is straightforward, benign and "natural." Obstacles include high initial cost (must withstand rodents and typhoon winds), the need for vigilant and regular maintenance in perpetuity, a likely requirement for concurrent rodent control, and the difficulty of emplacing barriers around steep cliffs.

Leads worth pursuing. Toxicants. The delivery system problem for toxicants needs to be solved. Hot-button issues on Guam are losses of non-target species (especially pets), cost and environmental contamination (especially groundwater).

Seductive losers. Trap capture is possible for short term, but cost is staggering if done in perpetuity. Best application is temporary protection.

Self-sustaining biocontrol has no particular advantages attributable to a reduced scale: why bother attempting at this scale if it does not work at larger scales?

Small Scale: Control Snakes Within Cargo Handling Yards, Transportation Craft, Etc.

Best tools. Visual searches are effective in visually simplified environments. Dog-aided searches are extraordinary sensitive, yet refinements in training and handling may be desirable, especially off Guam.

Exclusion is sensible for permanent protected zones and can be used on trees, buildings, power poles, forested patches and urban areas. Buildings can be made more or less snake-proof.

Traps are practical and refined, though numerous opportunities for improvement exist, both with basic design and low-cost attractants.

Repellents have their greatest value in flushing snakes from cargo that cannot be dismantled.

Fumigants are practical for high-risk cargo

Leads worth pursuing. Toxicants need further development, but could be very useful if of sufficiently low cost.

Seductive losers. None.

Summary

Islandwide control of the brown treesnake is a vague and distant hope. Islandwide eradication seems even less likely. Small-area control is in use now and in need only of further refinement. This means that preventing the spread of the snake to new islands is likely to be more effective than any other approach. However, this does not imply that there is no hope for Guam at a medium scale. Recent developments in barrier technology indicate that medium-scale protection can be arranged under some conditions. Breakthroughs in toxicants could make control or even eradication possible at modest scales. However, the inherent difficulties of registering rodenticides and ophiocides for the tiny Guam market suggest that any toxicant solutions are probably several years and $0.5 to $2 million in the future. Barriers have potential for use at a medium scale and, because they replace natural isolation in a technologically benign way, they have few obstacles in terms of technology development, registration or environmental contamination.

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